Intelligent Adaptive Interface: A Design Tool for Enhancing Human-Machine System Performances

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ABSTRACT

Intelligent Adaptive Interface (IAI) is a design tool that guides the development of an operator interface in enhancing human-machine system performance. With a set of design principles, this paper introduces the concept of IAI and its design framework, which include methodologies for developing various systems including operator interfaces. These methodologies are demonstrated in a case study where IAI framework was used in various design processes: mission scenario analysis, IAI function, task and goal analyses, identification of IAI agents, design of IAI components in a task network model for simulations, and implementation and evaluation of IAI prototypes. The efficacy of IAI was investigated in the context of controlling multiple Uninhabited Aerial Vehicles (UAVs). This case study proved that IAI framework and the associated design principles are effective in guiding the design of an operator interface. These principles are being applied in the development of an operator interface for the control of extremely agile micro-aerial vehicle employed in urban operations. They will be further used to guide the design of multi-modal operator interfaces for the control of UAV swarming. Additionally, these applications will provide empirical evidence to validate IAI design principles and thus enhance the robustness of this design tool.

1.0   INTRODUCTION

As automation technologies become critical elements of military activities, a robot revolution is upon us. It is a revolution in war, like the invention of the atomic bomb. More specifically, uninhabited systems (UVs) are robotic systems that are becoming more and more prevalent in all theatres of operations (land, sea, air, and urban). These robotic systems do not affect the "how" but the "who" of war fighting at its fundamental level. It changes and redefines the experience of the warrior and even his or her very identity. However, the role of the human remains paramount and the interaction of humans and this type of technological aid is critical to mission accomplishment. Net-enabled effects-based operations will place ever-increasing emphasis on the design of agile, intelligent, and socio-technical systems that allow more effective and efficient acquisitions and concept developments. Thus, the interaction with these robotic systems is vital. The key concepts here are "interaction" and "integration", human-robot interaction and human systems integration. If not enough attention is given to this very topic, then we may face social, ethical, and moral issues when confronting an entirely new species: robots. The challenge of Human-Robot Interaction and Human Systems Integration is to develop innovative tools, techniques, and methods that seamlessly work with the systems engineering and concept development processes to truly integrate knowledge of human capabilities and limitations [48].

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1.1 The Issue

Despite the pressing needs for effective socio-technical systems, there is still a lack of well-established design guidelines for these human-machine systems, especially for advanced operator interfaces used by decision-makers. The operator interface plays critical roles for dynamically managing enormous amounts of data and information in a complex and networked environment (e.g., network centric warfare). This correlates to an impediment of overall human-machine system performance. Additionally, a lack of integration between the Human Factors (HF) and Human Computer Interaction (HCI) domains has increased the tendency for terminology to become ambiguous and misleading when applied globally. Thus, there is a need to develop a unified framework to guide both researchers and practitioners in designing effective human-machine systems to enhance overall system performance.

To address the issue, Defence Research & Development Canada has completed a multi-year research program to develop a generic design framework to guide the design of operator interface in enhancing overall human-machine system performance. The efficacy of the framework has been assessed in the context of operator interface design for the control of multiple UVs from an airborne platform [22,23]. The framework is being used to guide the design of operator interface for the control of single micro-aerial vehicle employed in urban operations [18,21]. To further validate the design principles, the IAI framework is being applied and assessed to aid multi-modal interface designs for UV swarming. This paper describes this framework and a case study with a summary of research results.

1.2   Intelligent Adaptive Interface

Operator Machine Interface (OMI) technologies have been developed in different forms: from conventional interfaces to adaptive interfaces, and then to intelligent adaptive interfaces. In their most general form, conventional operator-machine interfaces are the medium between operators and a particular machine, device, computer program or other complex tools. The OMI facilitates the manipulation of a system and machine to produce the operator's desired effects.

The term "intelligent adaptive interface" (IAI) is adopted from intelligent interface and adaptive interface concepts [28,30,32,35,38,39,40,53,59]. Intelligent interface intends to capture the wide range of issues and methodologies from the application of intelligence to user interfaces, whereas the term adaptive user interface is used by many researchers to emphasize the adaptation of the interface [1,3,4,5,7,16,27,33,36,37,42,46,57]. Tomlinson et al. [56] defined adaptive interface as a manner to predict the features a user would find desirable and customizable. Thus, an intelligent interface should tailor its parameters to certain prescribed specifications or convert itself and adjust to changing circumstances, requirements or needs. In other words, it has adaptive capabilities (to the user and environment).

Adaptive interfaces are designed to individualize or personalize systems, thereby increasing the system's flexibility and effectiveness [20]. Thus, they are also known as personalizations to enhance operator interaction with a system by making the system more efficient, effective and easy to use. The interface is adapted (e.g., menu content) with the aim of matching its content to changing task-related circumstances (e.g., according to the mode selected and application used). The system controls whether the adaptation occurs, how it occurs, along with the amount of adaptation that occurs. However, the operator does not fully control how the system adaptation is initially configured.

Combining the concepts of intelligent and adaptive interfaces, an IAI can be defined as *a user interface with intelligence that can perceive, understand, reason, and infer relevant changes of environments and users, and adapt accordingly to facilitate its interaction with users.* IAIs are OMIs that dynamically change their control and/or display characteristics in reaction to a task and/or operator states in real-time [25]. The important issues to be addressed in IAIs [20] are:

- To formulate reliable and cost-effective IAI development methods;

- To develop the tools that enable easy development and maintenance of the intelligent parts of the system;

- To better understand how and when intelligence can substantially improve the interaction (design practice); and

- To establish usability principles for IAIs that do not lead users' expectations astray.

IAIs are epitomized by Microsoft's Office Assistant. This feature was included in Microsoft Office 1997 and subsequent versions until Office 2007. A 'popular' Office Assistant [52,6] is "Clippit" or "Clippy", which is a default animated paperclip. This feature is an entry point to the help system, presenting various help search functions and offering advice based on Bayesian algorithms [31]. Clippit will open when the program thinks that a user requires assistance. It will modify the formatting of the document and content of the menus accordingly. For example, when a user types an address followed by "Dear", a prompt Clippit is opened and states "It looks like you're writing a letter. Would you like help?" The algorithms would use a combination of task-based (e.g., how a letter is usually formatted) and user-based (e.g., how many mistakes the operator has made trying to write a letter) models to modify the interface to match the user's needs and requirements. Similar to adaptive interfaces, the amount of adaptation that occurs is controlled entirely by the system, although the user has some control over how the system adaptation is initially configured (e.g., the user can turn off Clippit).

Findlater & McGrenere [14] conducted an empirical study on adaptive user interfaces by comparing three menu conditions: static, adaptable and adaptive. Adaptive interfaces dynamically adjust the interface in a way that is intended to support the user (system controlled). By contrast, adaptable interfaces provide customization mechanisms but rely on the user to apply those mechanisms to initiate the adaptation (operator controlled). Each menu was implemented as a split menu but differed in the way the customization was implemented. Results indicated that the static menu was significantly faster than the adaptive menu due to its simple processing. The adaptable menu was also significantly faster than the adaptive menu due to its ease-of-use. The majority of operators preferred the adaptable menu because it is user-friendly. The implication to the Human Factors (HF) and the Human Computer Interface (HCI) communities is to determine which design approach (adaptive or adaptable interfaces) is the best. Some argue that easy-to-use predictable mechanisms should be provided to keep users in control of the system. Others believe that if the right adaptive algorithm is found, then operators will be able to focus on their tasks rather than managing their tools. Thus, easy-to-use mechanisms are not sufficient for effective customization (adaptive) and examples should also be provided to users for guidance on using the customization feature. Therefore, the lack of consistent design approaches in HF and HCI domains presents a challenge to designers to develop effective socio-technical systems.

2.0   IAI CONCEPTUAL FRAMEWORK

To develop a unified design framework encompassing both HF and HCI approaches, a thorough literature review was conducted to examine existing methodologies in the design of intelligent and adaptive interfaces/systems. The results are summarized in this section where the design principles are synthesized, condensed and reorganized. There are three categories to make them easy to follow: adaptation (A), interaction (I), and organization (O), or simply: AIO principles. A unified IAI framework was developed to describe detailed design principles using consistent and unambiguous terminology. A variety of analytical approaches to the development of an intelligent and adaptive agent-based system are also examined. These design approaches are CommonKADS (Knowledge Acquisition and Design Structuring) [51], IDEF (Integrated Computer Aided Manufacturing Definition) standards [44], Explicit Models Design [10], Ecological Interface Design [58], etc.

2.1 Adaptation (A)

The following design principles are synthesized from the literature related to adaptations [17,19,43,34,29,50,47,14].

A1: Appropriate adaptation cycles are required for automation to be turned on/off over a period of time.

A2: An IAI should dynamically change its level of autonomy according to the changes of the environment (including operator and task domains).

A3: Different types of reasoning tasks should be performed to solve problems in a variety of domains using a number of problem-solving techniques (e.g., logical inferences).

A4: An IAI must be able to reason a number of concurrent activities.

A5: An IAI should be able to integrate information over time to produce an accurate assessment of current situations.

A6: An IAI should be able to explain its behaviour in the time available.

A7: An IAI should have the capability to predict the effect of individual differences on task efficiency.

A8: An IAI should allow operators to override the system's choice of interaction mode and choose a mode that he/she prefers.

A9: An IAI should understand the human's actions relative to what it believes the operator is doing.

2.2 Interaction (I)

The following design principles are synthesized from the literature related to interactions between users and systems [17,43,34,15,45,50,54].

I1: Training in the use of IAI is necessary.

I2: The human operators should be able to rapidly reconfigure an IAI in response to changes in goals and problem-solving strategies.

I3: An operator should identify why the required level of accuracy could not be achieved as this information may affect future decisions.

I4: An IAI should make an operator feel 'in control', even when the IAI is performing tasks.

I5: An IAI should be able to generate and recognize plans.

I6: An IAI should monitor interaction for errors in performance and suggest a corrective action, which should be based upon an understanding of the error source and the probable intent of the operator in that context.

I7: Displays and controls should operate within a metaphor that is consistent with the operator's conceptual or 'mental' model.

I8: The interface should provide as much information as possible about any problem that could not be solved, such that the operator can judge the best course of action in the situation.

2.3 Organization (O)

IAIs share responsibility, authority and autonomy over system behaviour with a human operator. The aim of IAIs is to reduce operator workload and increase situation awareness. Although it is desirable for human operators to remain in charge (adaptable), they cannot be fully in charge of all system operations in today's complex systems. More specifically, humans cannot control the complex systems in the same way that they have been in earlier cockpits and workstations. Therefore, the following principles are related to the task allocations between an operator and a machine [41,47,55,2,12,13].

O1: Task and/or decision allocation should be completed according to the interaction of both mission goals and human/machine capabilities.

O2: IAI should initiate the off-loading of the task, and the operator should initiate the re-capturing of the task.

O3: An IAI should reduce cognitive workload by sharing the initiative for human-system dialogue.

O4: An IAI should support high levels of automation, while simultaneously allowing operators to remain in the decision loop and have an interactive role in the systems.

O5: An IAI should support the operator by monitoring input data for situations that indicate that the operator should be alerted, which suggests significant changes in the situation. The operator should be able to specify what the conditions may be.

O6: An IAI system should provide an operator with information that presents progressively more details as the situation demands and the operator should be able to take control.

O7: An IAI should provide operators with coordination of activities that are aimed at performing certain tasks and achieving specific goals.

O8: An IAI should provide operators with well-defined organization and structure, with members taking specific roles with associated power, authority and status, whilst exhibiting conformity and commitment to team norms and goals.

O9: An IAI should volunteer information to the operator and make responses appropriate to the operator's intent.

2.4 IAI Conceptual Framework

To conduct IAI designs, a framework is needed to indicate high level requirements of a system. A framework also shows the major components and the relationships among the components. By synthesizing the above mentioned AIO design principles, Hou, et al. [25] developed a conceptual framework as illustrated in Figure 1. This framework provides a comprehensive and efficient means of IAI design. The output of these processes

is the construction and specification of a number of models that are used to construct an intelligent adaptive system including an IAI:

- *Organization Model (O8).* This model incorporates knowledge relating to the organizational context in which the knowledge-based system is intended to operate (e.g., command and control, structures, Intelligence Surveillance, Target Requisition and Reconnaissance - ISTAR etc.);

- *Task Model (O1-3).* This model incorporates knowledge relating to tasks and functions undertaken by all agents, including the operator;

- *Agent Model (A6-7, A9, I5, O4-5, O9).* This model incorporates knowledge relating to the participants of a system (i.e., computer and human agents), as well as their roles and responsibilities;
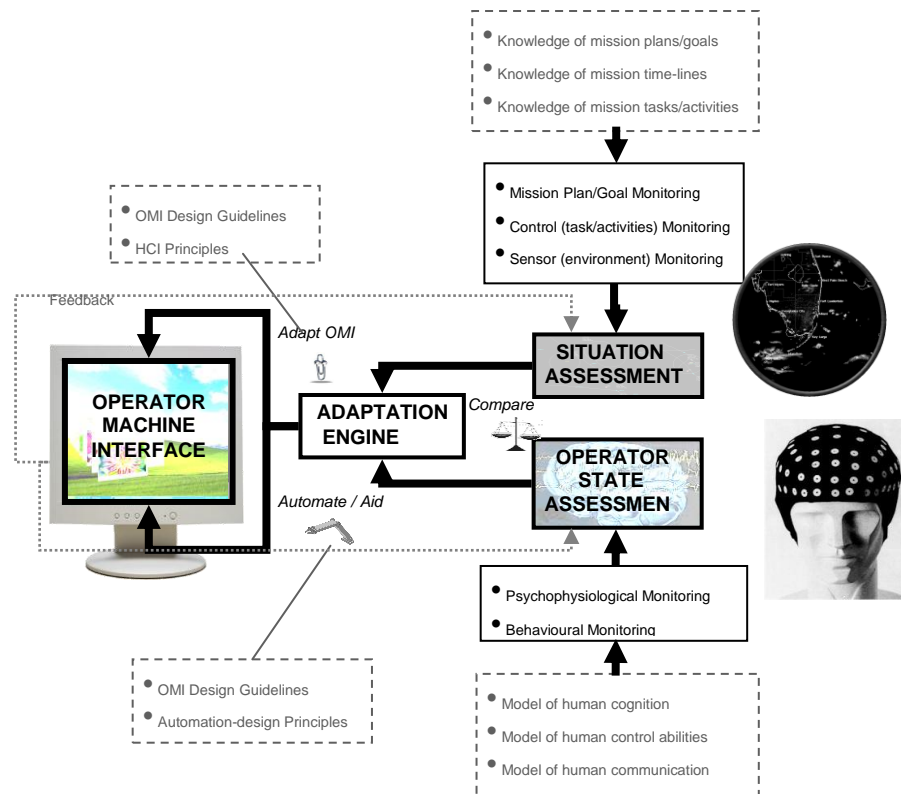

Figure 1. IAI Conceptual Framework [25]

- *User Model (A7-9, I1-4, O5, O9).* This model incorporates knowledge of human operators' abilities, needs and preferences;

- *System Model (A4-5, I5-6).* This model incorporates knowledge of the system's abilities, needs, and the means by which it can assist the human operator (e.g., advice, automation, interface adaptation);

- *World Model (A1-3, O5-8).* This model incorporates knowledge of the external world, such as physical (e.g., principles of flight controls), psychological (e.g., principles of human behaviour under stress), or cultural (e.g., rules associated with tactics adopted by hostile forces) environments;

- *Dialogue/Communication Model (I5-8).* This model incorporates knowledge of the manner in which communication takes place between the human operator and the system, and between the system agents themselves;

- *Knowledge Model (A3, A5-7, I6).* This model incorporates a detailed record of the knowledge required to perform the tasks that the system will be performing; and

- *Design Model (A8, I7-8).* This model comprises the hardware and software requirements related to the construction of the intelligent adaptive system. This model also specifies the means by which the operator's state is monitored.

3.0   ANALYTICAL METHODOLOGIES

To build a complex system like IAI, high-level design principles must be combined with thorough analytical methodologies. These methodologies are the tools used to analyze and build various models shown in Figure 1. These models represent system components or functions at different operational levels. The analytical processes and relationships among various methodologies and models are illustrated in Figure 2. These models should enable system functions to:

- Modify OMI to handle the interaction and dialogue between an operator and system components or software agents;

- Track the operator's goals/plans/intents (and progress towards them);

- Monitor the operator state;

- Monitor the world state; and,

- Provide knowledge of the effects of system advice, automation and/or adaptation on the operator and world states (i.e., closed-loop feedback).

Additionally, the models illustrated in Figure 2 can be mapped back onto the generic IAI conceptual framework in Figure 1. These models are necessary to effectively facilitate operator-system interaction. The User Model enables the monitoring of the operator's behaviour and physiological states. The Task, System, and World Models enable the monitoring of mission plan/goal completion, tasks/activities, and entities and objects in the external environment. The Knowledge Model enables the system to provide advice to the operator, automate tasks, or adapt to the OMI. The Dialogue Model enables an effective interaction between the system and the operator. The generation of these models is one of the implementation steps of the generic conceptual framework. Figure 2 also illustrates various analytical approaches which can contribute to the creation of different models, specifically:

- *Cognitive Analysis Methodologies,* contribute to the construction of the Task, Agent and User Models;

- *Task Analysis Methodologies,* contribute to the construction of the Task, Agent, System and World Models;

- *Human-Machine Function Allocation and Agent-based Design Principles,* contribute to the construction of the Agent, Dialogue and Communication Models;

- *Human-Machine Interaction and Organization Principles*, contribute to the construction of the Dialogue and Communication Models;

- *Human Factors and Human Computer Interaction Principles,* contribute to the construction of the OMI and related systems. The design process might also include principles from Ecological Interface Design.

- *IDEF5 Guidelines*, contribute to the construction of the ontology and knowledge base. This is then used to enumerate the knowledge captured by the analysis process;

- *Domain Feasibility, Cost‑Benefit Analysis and Principles for Closed-Loop Implementation,* contribute to the construction of the Design Model, including the means by which operator state is monitored; and

- *Human Factors and Human Computer Interaction Principles,* contribute to the construction of the OMI and related systems. The design process might also include principles from Ecological Interface Design.
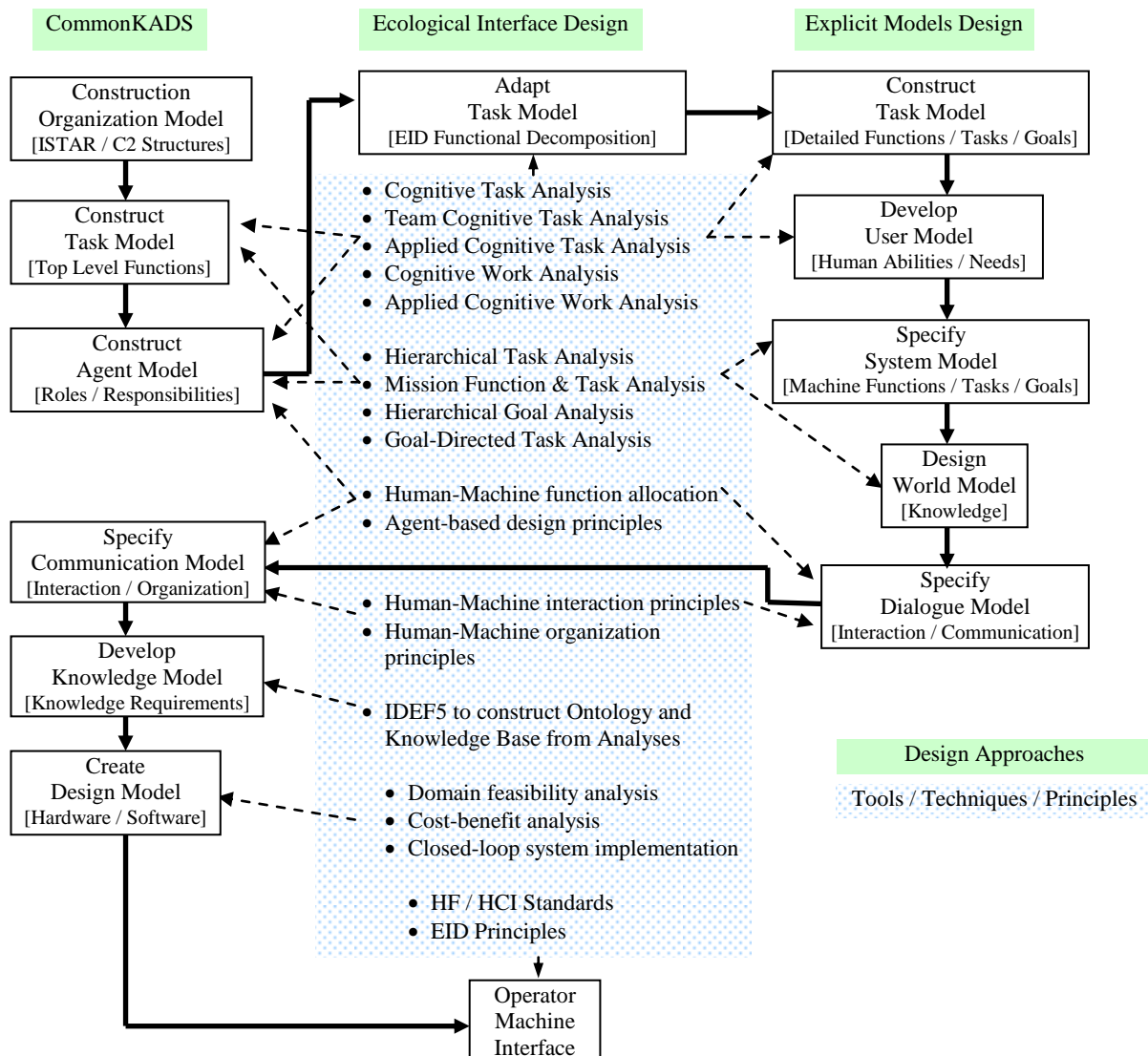
Figure 2. The Analytical Process for the Development of Intelligent Adaptive Interface

Most analytical approaches are generic (i.e., context independent) and scalable. The selection of these analytical tools is less critical as they can be (and sometimes must be) modified to suit the domain. Further, these analytical approaches can be combined to play to their strengths and mitigate weaknesses. Several criteria can be used to determine which analytical and design tools, techniques, and methodologies should be used to design a specific intelligent adaptive interface:

- Project constraints: schedule and budget.

- Domain: complexity, criticality, uncertainty, and environmental constraints (particularly relevant to the choice of operator state monitoring systems).

- Operator: consequences of error and overload, what kind and quantity of support is needed, who needs to be in control (particularly relevant in combat domains).

- Tasks: suitability for adaptation, assistance or automation.

4.0   CASE STUDY: IAI FOR THE CONTROL OF MULTIPLE UAVS

4.1.   The Requirement of Interface Design for the Control of Multiple UAVs

UAV control is operator intensive and can involve high levels of workload. As the quantity and variety of data collected increase, the workload for UAV operators increases significantly. Moreover, the allocated data must be integrated and/or converted into information and then disseminated to those operators who make decisions. In the recent past, data collection, data fusion, information management and distribution, intelligence collecting, and data-related decision-making have threatened to become a bottleneck. This situation is made even more complex by increasing joint operations, and rapid and flexible warfare. Feedback from the UAV operators indicate that improvements in the operator interface aspect of these emerging systems would reap significant gains in system performance and effectiveness. This applies for both effective control of UAVs, as well as management of data and efficient dissemination of the associated information. The level of automation to be applied to the decision-making processes is a key aspect facing both tactical commanders and UAV system managers. As a result, supporting technologies that combine operators with automation to satisfy mission requirements need to be investigated.

4.2   Issues

The control of multiple UAVs is a complex cognitive task with high workload. Applying the above mentioned IAI framework into the design of these advanced human-machine systems will likely provide a real potential for improvement in the effectiveness of UAV control. To investigate the efficacy of the IAI framework, the IAI associated design principles were applied into operator interface design for the control of multiple UAVs from an airborne platform. The issues to be addressed in this case study include the components of the framework that are required to analyze scenarios, missions, goals and whether the framework is effective in conducting the development of the UAV control system.

4.3   The Use of IAI Framework as Design Guidance

IAIs are applied here for reducing operator workload and improving decision effectiveness in the employment and operation of UAVs. IAIs are human–machine interfaces that aim to improve the efficiency, effectiveness, and naturalness of human–machine interaction by acting adaptively and proactively in response to external events based on internal mission requirements. In the context of UAV control, an IAI is driven by software

agents that support the decision-making and action requirements of operators under different levels of workload and task complexity. The IAI manifests itself by presenting the right information, action sequence proposals, or by performing actions at the right time. In addition to reducing workload for humans involved in UAV missions, IAI is seen as an opportunity to reduce manning requirement (e.g., moving from ratio of 10 operators controlling one UAV to one operator controlling 10 UAVs).

4.4   How the Framework Was Used

As a standard systems engineering approach, the IAI framework was used from the starting point of the operator interface design: analysis. For systems where human functions are predominantly "cognitive", the method of analysis should capture this essential human activity. IAI framework was used in the following design processes:

First, operational mission scenario generation. A fictitious counter-terrorism scenario was developed for a maritime patrol task along the east coast of Canada. The scenario involved a UAV crew controlling multiple UAVs from airborne platform CP140, which is a maritime patrol aircraft. The UAV crew consisted of three operators: UAV pilot (UP), sensor operator (UO), and tactical navigator (TN). The UAV pilot was responsible for the safe and appropriate conduct of all UAVs under the crew's control. The UO was responsible for managing the information being returned by the sensors onboard the UAVs under the crew's control, and for relating findings based on that sensor data back to the rest of the crew as appropriate. The TN was ultimately responsible for overall operations. According to the nature of tasks each crew member performed, three levels of the task complexity were assigned: low (UP), medium (UO), and high (TN). Depending on the number of UAVs to control, workload was also assigned at three levels: low (one UAV), medium (two UAVs), and high (five UAVs).

Second, Operational Sequence Analysis. To understand the logical interconnection of operators' tasks and the flow of information throughout the system during the conduct of the mission scenario, operational sequence diagrams (OSDs) were used to show the flow of information and operator functions through the system in relation to the mission timeline. The visual representation of OSDs indicated actions, inspections, data manipulation (i.e., transmission, reception, and storage), time delays, and decisions of the mission scenario. Thus, OSDs are particularly useful for the analysis of highly complex systems that require many time-critical information-decision-action functions by multiple users, which is the case for this study [22]. With the scenario written, a series of OSDs were prepared to facilitate a function and goal/task analysis of the envisaged system and the development of a model from which performance predictions could be made and the potential for IAI automation agents to be identified. These OSDs also created an inventory of all bottom-up lowest level tasks in a temporal sequence. A small portion of an OSD as an example of the operational network between three UAV operators is shown in Figure 3.
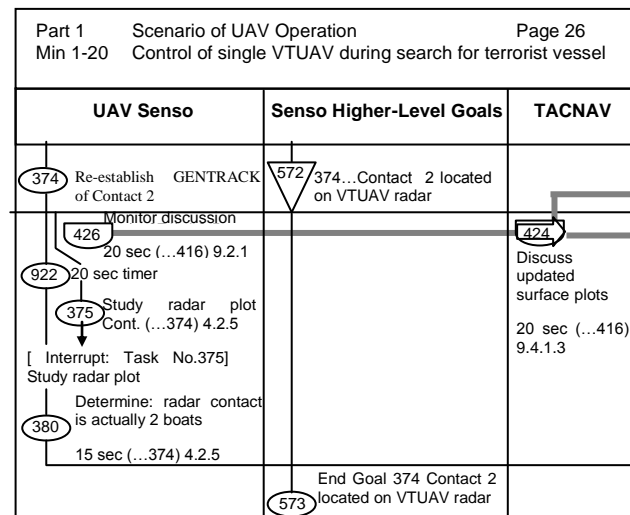
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┌────────────────────────────────────────────────────────────────────┐
│ Part 1      Scenario of UAV Operation                    Page 26     │
│ Min 1-20    Control of single VTUAV during search for terrorist vessel│
├──────────────────────────┬────────────────────────────┬─────────────┤
│      UAV Senso           │  Senso Higher-Level Goals  │   TACNAV    │
│                          │                            │             │
│ (374) Re-establish GENTRACK │ (572) 374…Contact 2 located │             │
│       of Contact 2       │       on VTUAV radar       │             │
│        Monitor discussion│                            │   (424)     │
│      (426)               │                            │             │
│           20 sec (…416) 9.2.1│                        │  Discuss    │
│ (922) 20 sec timer       │                            │  updated    │
│         (375) Study  radar  plot │                    │  surface plots│
│               Cont. (…374) 4.2.5 │                    │             │
│                          │                            │  20 sec (…416)│
│ [ Interrupt:  Task  No.375] │                         │  9.4.1.3    │
│ Study radar plot         │                            │             │
│           Determine: radar contact │                  │             │
│      (380) is actually 2 boats │                      │             │
│           15 sec (…374) 4.2.5 │                        │             │
│                          │        End Goal 374 Contact 2 │          │
│                          │ (573) located on VTUAV radar │           │
└──────────────────────────┴────────────────────────────┴─────────────┘
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Figure 3. A sample of Operational Sequence Diagrams [22]

Third, hierarchical goal analysis (HGA). Research on IAIs in the military research and development community was limited when this work was conducted. As a result, the work began with an HGA within which standard mission, operation, and goal analysis procedures were followed to gain more detailed understanding of implementation issues and opportunities for IAI tasks that can be automated. A particular interest in this work is the identification of goals that are candidates for IAI automation agents. Using the AIO principles and IAI framework, the *agent, user, system, and world* models were created. Upon the completion of the scenario and OSDs, a hierarchical decomposition of the envisaged system goals was conducted. The goal decomposition for all three UAV operators took place according to a means-end hierarchy and the needs of analysis were typically satisfied at the fourth or fifth level in this exercise. The goal decomposition was first performed in a top-down fashion from the highest level (e.g., GOAL= counter-terrorist mission is completed) down to lower levels (e.g., GOAL= Vertical Take-off UAV sector search is planned). Then, a more stringent bottom-up approach was completed with the study of the detailed mission activities in OSDs. As a result, more goals were added in the top-down analysis list to complete the generation of the HGA inventory. An example of a small portion of HGA results is illustrated in Table 1.

Table 1. An Example of HGA Results [22]

Number	Level				Goal/Objective and Sub-goals/Sub-objectives	IAI Candidate	Influenced Variable	Assignment	Completion Time (Sec)
	1	2	3	4	5				
Top	I want to perceive the (...) conduct of the terrorist patrol mission								
9	**...**				**communications are conducted and maintained**				
9.1		...			directions (instructions) are received				
9.1.1				... directions are received from other crew members		Yes	Directions	UAV Pilot	4 to 25
9.1.2				... directions are received from other units		Yes	Directions	UAV Pilot	5 to 14
9.2		...			information is received				
9.2.1			...		information is received from other crew members				
9.2.1.1				... VTUAV refuelling location			Location	Tactical Navigator	5
9.2.1.2				... VTUAV calculated time on task		Yes	Time	Tactical Navigator	5
9.2.1.3				... the flight crew's message that contact is identified			Message	Sensor Operator	5

Fourth, task network modelling and simulation. Following the generation of OSDs and the HGA, tasks related to a system that can be automatically operated (with automation intelligence or expert knowledge) were chosen to be appropriate IAI automation agents. Goals for systems that have no information on automated operations could not be identified as IAI automation tasks. With the identification of these IAI tasks/agents, a task network model was developed in an Integrated Performance Modelling Environment (IPME). IPME is a discrete event-simulation framework used to model and assess human and system performance [8]. It comprised an environment model, a crew model, a task network model, a performance-shaping model, and optional external models. Combined with IPME's scheduling algorithm, these models can help an analyst predict workload and operator performance. An IPME database was also generated while producing the OSD and HGA tasks. In the database, each task was allocated to an operator or a system with a descriptive label. With the database, a sequential type of operational network model was developed. Although the network model was a UAV operator model, external events (other aircrew activities, UAV activities, and other unit activities) had to be established to allow the network to function as a closed-loop feedback system. These were prepared and included in the network which was used to define task behaviour, operator assignment, and interactions between tasks and operators. By linking together various networks or tasks, the model attempts to replicate the behaviour of a real system. The task network model was run 10 times in IPME to simulate the mission conducted. The simulation data collected were used to analyze operators' behaviours and determine the effects of IAI agents on operators' performances. The IAI models provided not only an effective means to assess the merits of incorporating new automation technologies, but also a clear indication of the most fruitful areas for further research and developments.

Fifth, the human-in-the-loop experimentation. The IAI framework and related AIO principles were used to analyze mission scenarios, identify IAI tasks, and generate task network models. The simulation study was considered as initial estimates of IAI agents being augmented decision-aids, but further analysis regarding the most beneficial IAI tasks to modify was required. Additionally, considerable effort was still needed to apply IAI framework and related AIO principles to design prototype systems. Strong empirical evidence was also required to substantiate this effort. Thus, an experimental synthetic environment (SE) was designed and developed to conduct a human-in-the-loop experiment and validate the task network modelling method used in the simulation. Consistent with the UAV crew positions used in the performance modelling phase, the SE

had three control consoles replicating CP140 tactical compartment multifunction workstations. The workstations were designed to communicate with virtual UAVs through fully functional, real world software interfaces. Each of them had a set of appropriate displays and controls for the UP, UO, and TN as illustrated in Figure 4. The experimental environment also had the ability to integrated video and audio data collection, thus enabling empirical assessments of IAI concepts developed in the first phase.
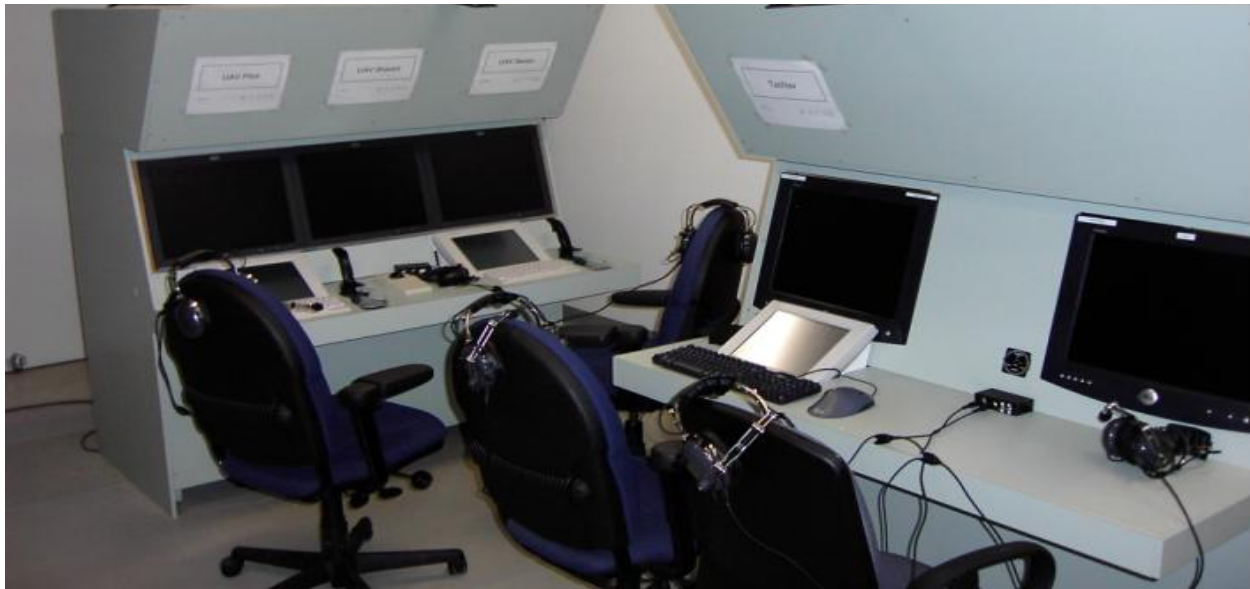

Figure 4: Experimental Environment Showing Three UAV Control Stations for UAV Pilot, Sensor Operator, and Tactical Navigator [26].

The IAI agents were functional components of the UAV control SE developed for this research. They supported the participants in accomplishing the assigned mission tasks of the experiment by providing decision support to the crew and by taking over certain high workload crew tasks. A 3 x 3 x 2 (Operator Workload: one UAV vs. two UAVs vs. three UAVs; Operator Position Complexity: UP vs. UO vs. TN; IAI Interface Condition: ON vs. OFF) mixed-factor design was used in the experiment, as illustrated in Figure 5. The IAI for each crewmember was tailored to suit their individual needs. Both Operator Workload and IAI Interface Condition were within-subjects factors, meaning that participants were tested under all levels of those factors, whereas Position Complexity was a between-subjects factor (i.e., crewmembers remained at one position throughout the experiment).
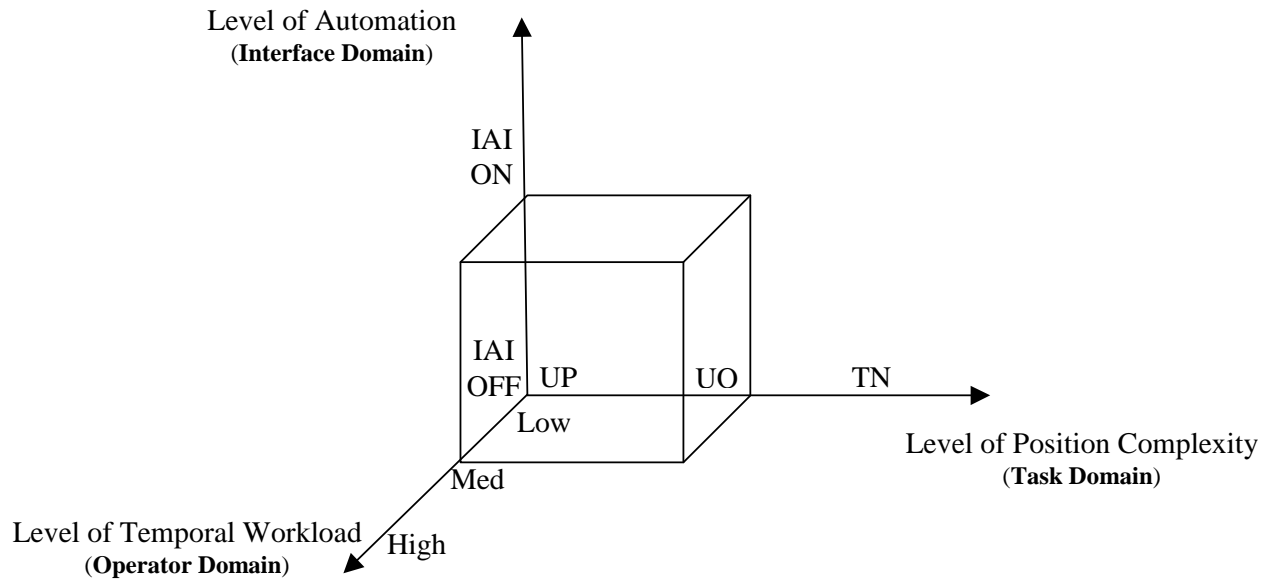
Figure 5: Depiction of the Mixed-Factor Experimental Design [26].

4.5   Discussion and Implications

Although the IAI implemented as a prototype system in this case study was only a small subset of a future, more extensive suite of a fully optimized agent system, the experimental findings indicated that the control of a dynamic and complex system such as multiple disparate UAV control from an airborne platform can be improved through the use of a multi-agent IAI suite. More importantly, through the discussions and observations made during the conduct of the study, experience and knowledge were gained regarding the use of IAI framework and associated AIO principles for the design of IAI agents, the implementation of synthetic IAI prototype environments, and the conduct of the experiments. Many thoughts were also given to the details of IAI design issues which were discussed in Hou, Kobierski, and Herdman [26].

This case study on IAI design for the control of multiple UAVs demonstrated that the proposed IAI framework and associated AIO principles provided useful guidance for IAI developments. The framework is *complete*: the principles, the models and the analytical methodologies covered all the tasks related to the entire design and evaluation cycle of a human-machine system; *consistent*: the principles, the models and the analytical methodologies keep a consistent track from abstract guidelines to concrete models and methods; *effective*: the framework speeds up the design and execution of the experiment in both time and personal management because of the clear division between the principles and models; and *user-friendly*: the analytical methodologies in Figure 2 provides clear processes for the system design.

With the successful use of IAI framework in the operator interface design for the control of multiple UAVs, related design principles are being used in broader fields including operator interface design for the control of an extremely agile micro-aerial vehicle (EA-MAV). Having an EA-MAV that can be controlled in-theatre means an infantry section can receive reconnaissance quickly and have information delivered to operators who need it most. To best use such technology, operators require a ground control system (GCS) to interface with the flying machine they are controlling. The GCS itself is subject to stringent engineering criteria, such

as the need to be robust enough to withstand heat extremities, moisture, and impact. Additionally, an OMI must be intuitive in function and easy to learn for average soldiers. If the OMI is not optimized, there is potential for loss of systems and time during mission-critical moments as operators attempt to decipher what the next control sequence should be. Further, the GCS must be small and light enough to avoid serious burden to the operator who will be carrying it. Keeping these requirements in mind, IAI framework is being used to design and develop an operator interface on handheld devices. Similar to the design process of IAI for the control of multiple UAVs, a mission scenario was developed to represent the typical use of EA-MAV for infantry solders. This time, cognitive task analysis was used to identify function groups for IAI automation agents. AIO principles were used to develop user, task, system, environment, and agent models. Figure 6 shows a snapshot of an OMI on a tablet PC.
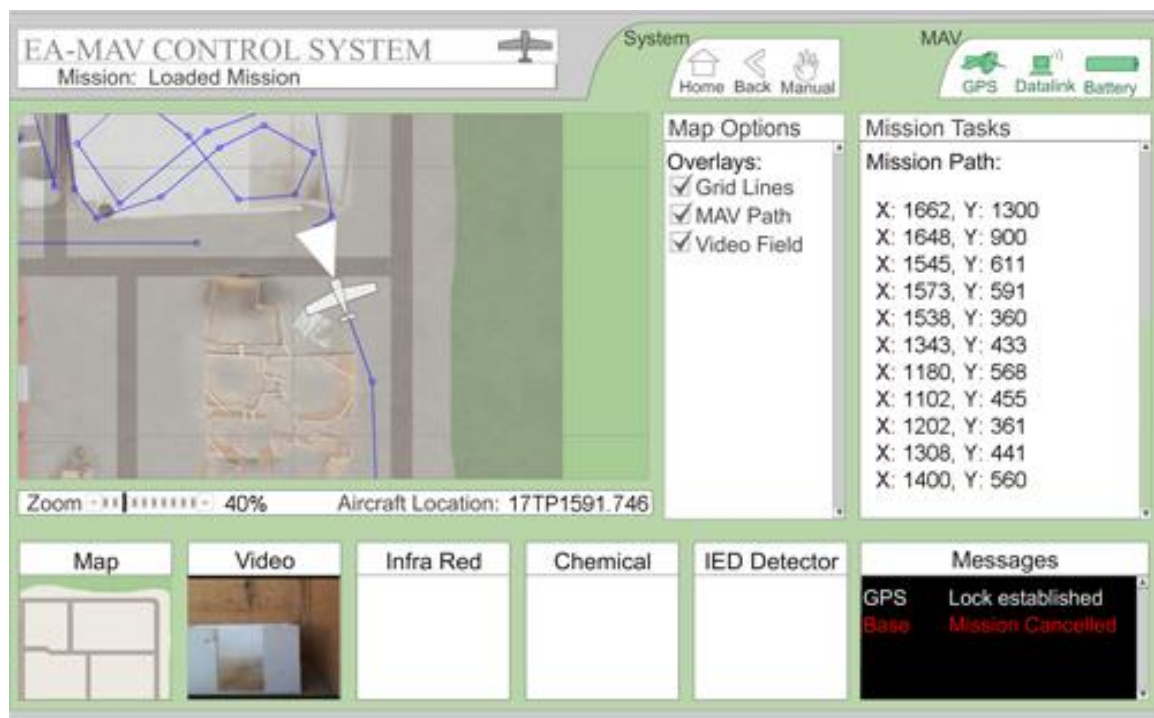

Figure 6. A Snapshot of OMI on a Tablet PC for the Control of EA-MAV [21].

The prototype interfaces will connect to a synthetic 3D environment where a virtual EA-MAV can be controlled by handheld devices. An example plan for an empirical investigation was developed to determine how using a device with tactile hardware buttons, as opposed to a touch screen input device, affects the performance of an EA-MAV operator. The findings will not only assist in choosing the optimal input and display method and thus an effective OMI for the final GCS system, but will also provide design guidelines for the control of EA-MAVs using handheld devices. The design processes will also validate the IAI framework and associated principles for OMI design.

5.0   CONCLUSIONS AND FUTURE WORK

The IAI framework provides guidance to the effective design of OMI. Through the IAI design case study for the control of multiple UAVs, IAI framework and associated AIO principles have proven to be an effective design tool to guide the design process and thus enhance human-machine system performance. They contributed to the Canadian Forces Air Force automation policy and planning developments. They are being used to design OMIs for the control of an EA-MAV to address situation awareness in an urban operation scenario. Although many analytical approaches and design models have been used, there are still some models that have not yet been completed (e.g., human cognition model for physiological monitoring) due to the immaturity of relevant technologies (e.g., Augmented Cognition). Thus, IAI framework and associated AIO principles still need to be further developed and validated within different contexts. More empirical studies are still required to enhance the robustness of this design tool. To accomplish this goal, IA framework will be applied to design OMIs for a complex, synthetic environment where a network-enabled operations approach will be used for the control of various UVs. The IAI framework will also guide a study of multi-modal OMI design for the control of UV swarming to reduce human error and improve human performance. These investigations will further validate IAI design principles and refine customized approaches for different applications. The revised principles will contribute to the standardization of operator interface design principles and facilitate interoperability across many military systems.

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